Effect of Electron Beam Freeform Fabrication (EBF^3) Processing Parameters on Composition of Ti-6-4

Cynthia L. Lach, Karen Taminger and A. Bud Schuszler II
NASA Langley Research Center

Sankara Sankaran
Lockheed Martin

Helen Ehlers, Rahbar Nasserrafi, and Bryan Woods
Spirit AeroSystems, Inc.

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Cynthia.l.lach@nasa.gov

Ti6-4 EBF^3 Team Contributions

- **NASA Langley Research Center**
  - Developed and conducted Ti-6-4 EBF^3 depositions (single bead and multi-bead) for processing study
  - Sample preparation and specimen photography
  - Metallographic analysis
  - Multi-bead micro-chemical analysis (wavelength dispersive spectroscopy)

  Cindi Lach, Karen Taminger, Bud Schuszler II and Richard Martin (NASA)

  Sankara Sankaran, David Hartman, and Jim Baughman (Lockheed Martin)

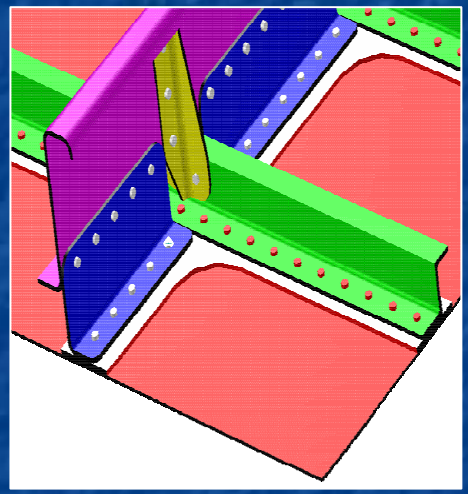
- **Spirit AeroSystems, Inc.**
  - Single-bead bulk chemistry analysis (inductively coupled plasma technique; samples provided by NASA LaRC)
  - Correlation of single bead deposit chemistry with processing parameters

  Helen Ehlers, Rahbar Nasserrafi, and Bryan Woods

Evolution of Metallic Aerospace Structures: EBF^3 Enables Paradigm Shift in Design

Designed for Assembly

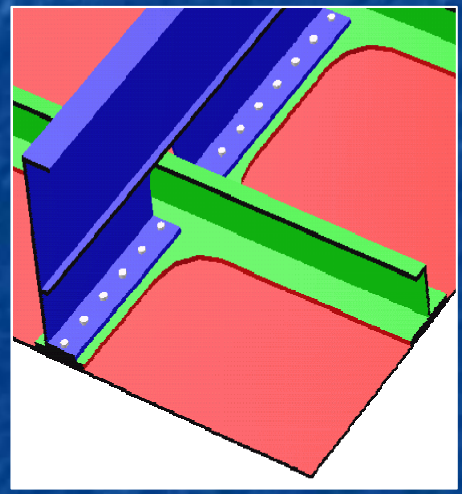
Built-up Structure



- Skin and stiffeners machined from plate
- Multiple parts and fasteners

- High:cost, scrap, weight, and assembly time

Integrally Stiffened

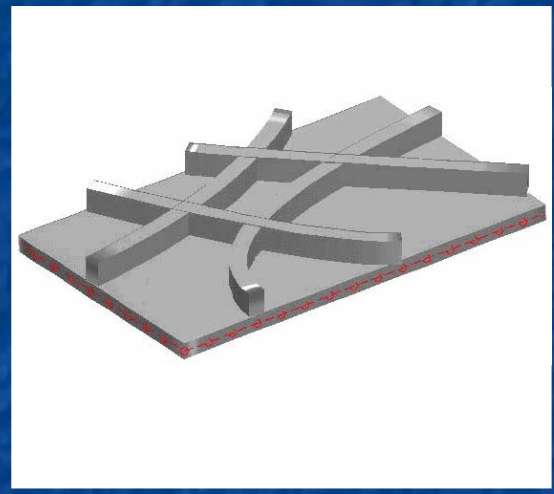


- Skin machined from sheet & integrated with near net stiffeners (SPF, extrusions, etc.)
- Replace fasteners (FSW, RSW)

- Reduce: cost, weight, parts, fasteners, and assembly time

Designed for Performance

Unitized Structure



- EBF3 combines fabrication of material+structure
- Enhanced performance through multi-functional novel design

- Minimize: scrap, weight, fasteners and assembly time

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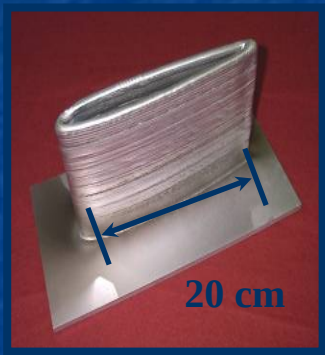
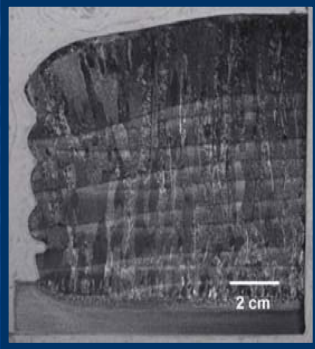
Electron Beam Freeform Fabrication (EBF^3) Capability at NASA LaRC





Capability

- Computer controlled, electron beam gun (42kW), dual wire feed, 6-axis positioning, in a high vacuum
- Build envelope (6'x 2'x 2') with a heating platen (900°F)

Process

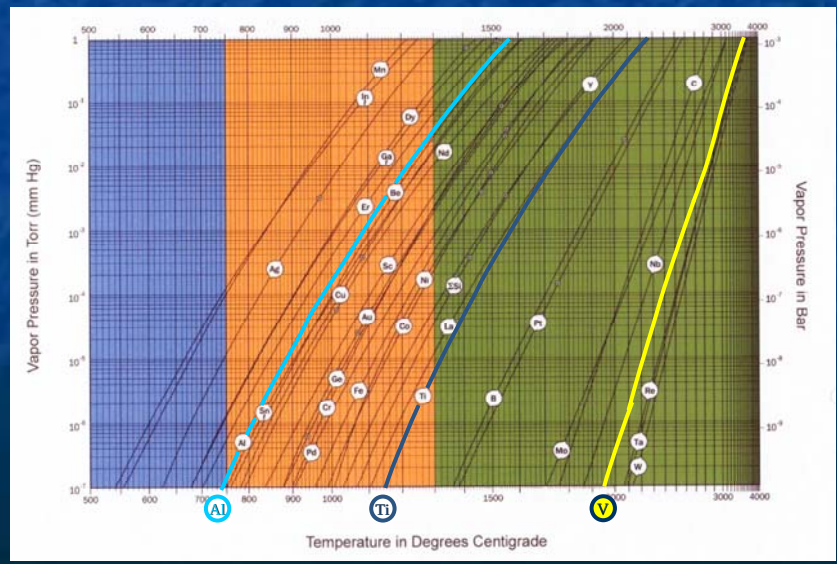
- Layer-additive process: wire fed into molten pool created by an electron beam (100% dense)
- Built from a CAD file: 2-D slices representing 3-D object
- Produces near-net shape parts with material properties equivalent to annealed wrought product

Cynthia.l.lach@nasa.gov

Challenges of Molten Pool Processing in a Vacuum

- EBF^3 process occurs in a high vacuum (10^{-5} torr) and requires sustaining a molten pool
- EBF^3 of Ti-6-4 processing occurs at 1800^{o}F above melting temperature of the alloy
- Selective vaporization of Al occurs
- Study conducted to understand the influence of processing parameters on composition and microstructure changes related to Al loss

Variation in Vapor Pressure of Elements with Temperature



Cynthia.l.lach@nasa.gov

EBF^3 Process Development for Ti-6-4

Objectives

- Optimize EBF^3 processing parameters to avoid selective vaporization of Al
- Evaluate deposit chemistry and microstructure as a function of beam power, wire feed & translation speed

Approach

- Conduct a Design of Experiment (DOE) to identify process parameter ranking and interactions
- Composition analysis (Bulk and Micro-chemistry)
- Conduct systematic trials (single/multi-bead) of outer processing envelope limits

Cynthia.l.lach@nasa.gov

Design of Experiment (DOE) Approach to Control the EBF^3 Process and Reduce Variation

Taguchi Design (L27)

- 3-Factorial, 3-Level design (fully balanced, mutually orthogonal array)
- Ability to separate and rank effects of each parameter and any interactions
- Randomly selected deposit schedules

Process variables (3 parameters @ 3 levels)

- Beam Power (BP): Baseline, 2 and 3 times
- Translation Speed (TS): Baseline, 2 and 7 times
- Wire Feed Rate (WF): Baseline, 4 and 8 times

Process Constants

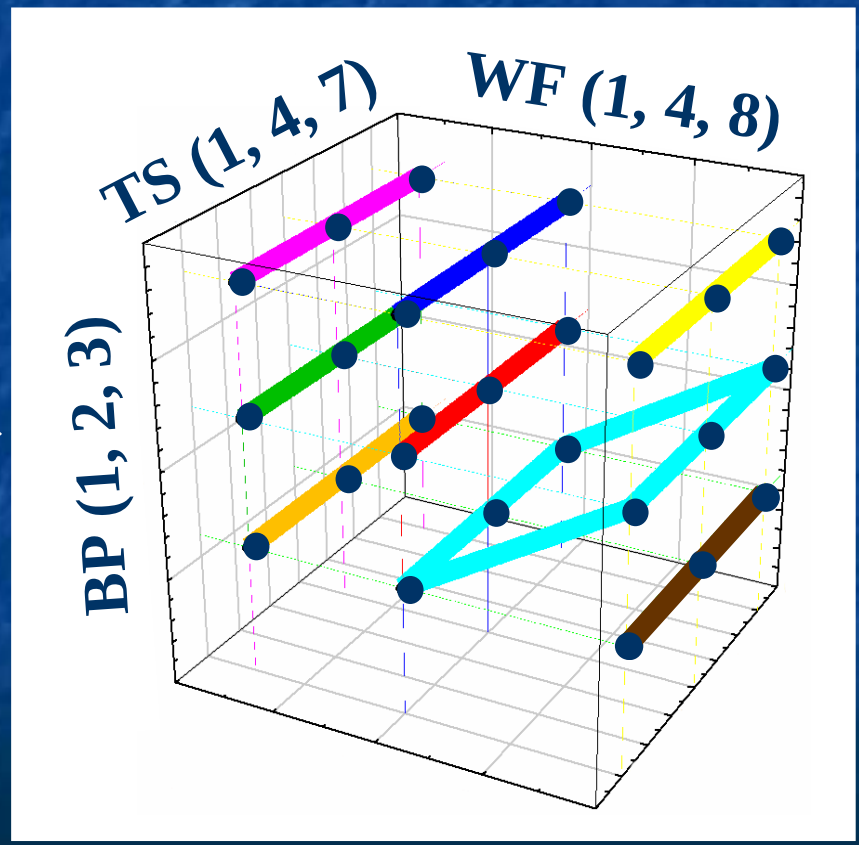
- Voltage, Focused Beam, Wire diameter (0.063 in), Acid cleaned base plate (0.39 in), Preheat , Deposited same day at temperatures $\leq$ 150^{o}F

Processing Envelope Energy Density (ED) Levels per Unit Volume of Material Deposited

- Taguchi 3x3 matrix
- Conducted randomly

- ED = BP/[Area WIRE *WF*time], kW/in^3
- ED levels varied from baseline to 24 times

Run #	Beam Power	Translation Speed	Wire Feed Rate
1	High	High	High
2			Medium
3			Low
4	High	Medium	High
5			Medium
6			Low
7	High	Low	High
8			Medium
9			Low
10	Medium	High	High
11			Medium
12			Low
13	Medium	Medium	High
14			Medium
15			Low
16	Medium	Low	High
17			Medium
18			Low
19	Low	High	High
20			Medium
21			Low
22	Low	Medium	High
23			Medium
24			Low
25	Low	Low	High
26			Medium
27			Low



Bulk Chemistry Analysis of Ti-6-4 EBF^3 DOE Single-bead depositions

- Single layer deposits produced at NASA LaRC
- Bulk analysis conducted on material excised from deposit bead only
- Bulk chemical analysis performed by Spirit AeroSystems, Inc. using ICP
  - Al, V, Ti, and Fe

Bulk Chemistry Analysis of Ti-6-4 EBF^3 DOE (3x2) Single-bead depositions

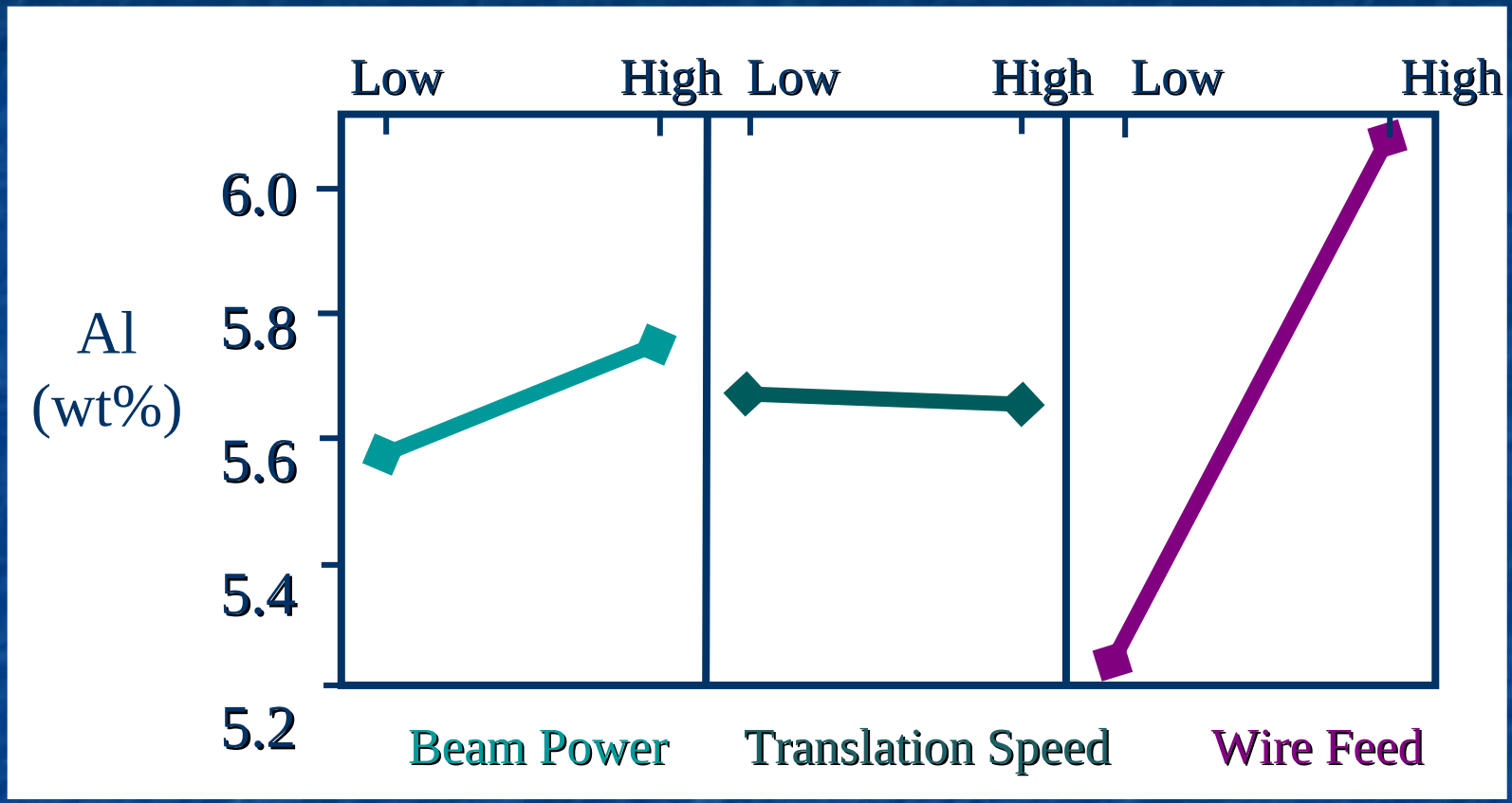
Subset: 3 parameters at 2 levels

				Al wt%	V wt%
Ti-6-4 Specification Limits				5.50 - 6.75	3.50 - 4.50
Base Plate				6.25	3.87
Wire				6.39	3.81
Run #	BP	TS	WF		
1	High	High	High	5.95	4.00
3	High	High	Low	5.05	4.24
7	High	Low	High	6.12	3.96
9 *	High	Low	Low	5.87 *	4.10
19	Low	High	High	6.54	4.24
20	Low	High	Low	5.07	4.10
25	Low	Low	High	5.71	3.81
27	Low	Low	Low	4.97	3.97

- For WF = Low Al wt% < specification limits (except # 9)
- Average Al wt% in DOE schedules = 5.66 wt%
- Drop in Al content varied (0.27 – 1.42 %)

Cynthia.l.lach@nasa.gov

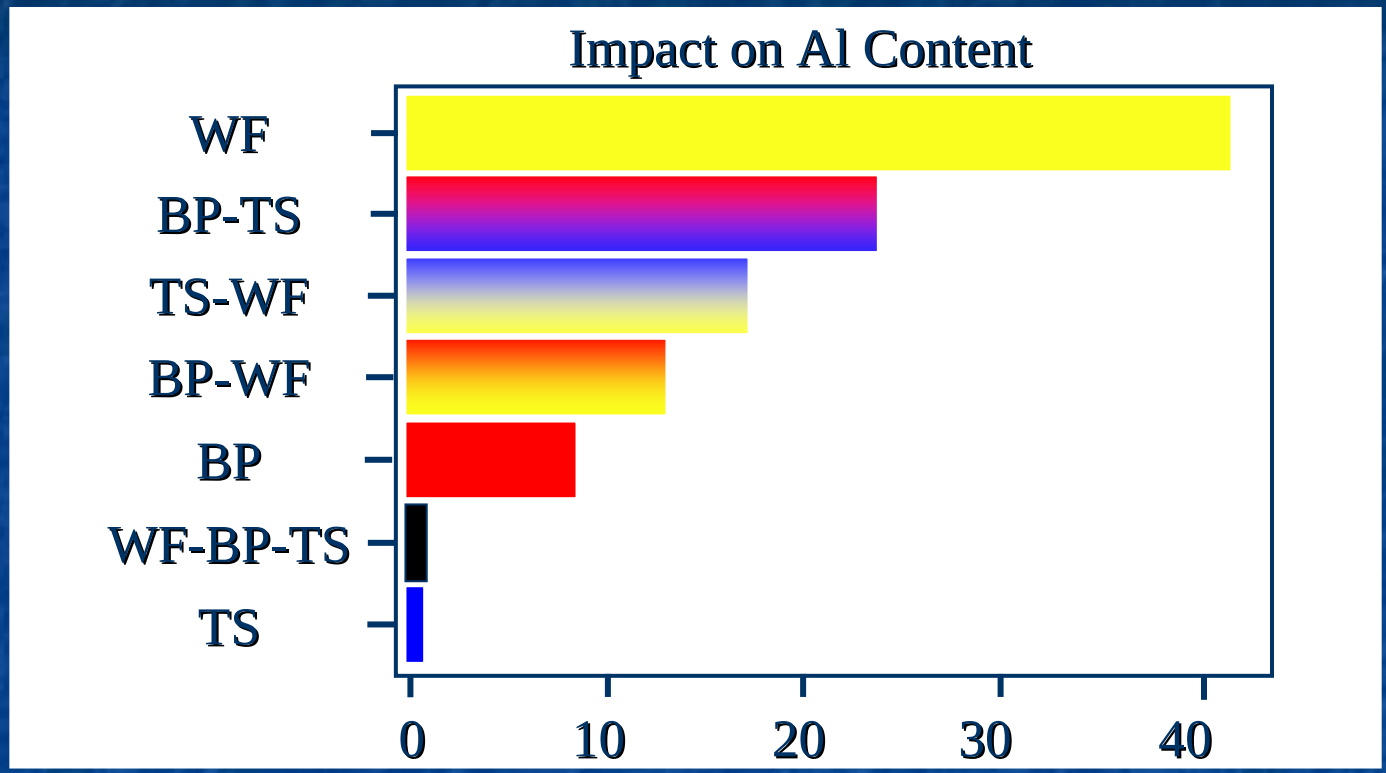
Effect of EBF^3 Process Parameters on Al Content



- Wire Feed rate has the greatest impact on Al content
- Beam Power also plays a significant role
- Translation Speed is insignificant

Cynthia.l.lach@nasa.gov

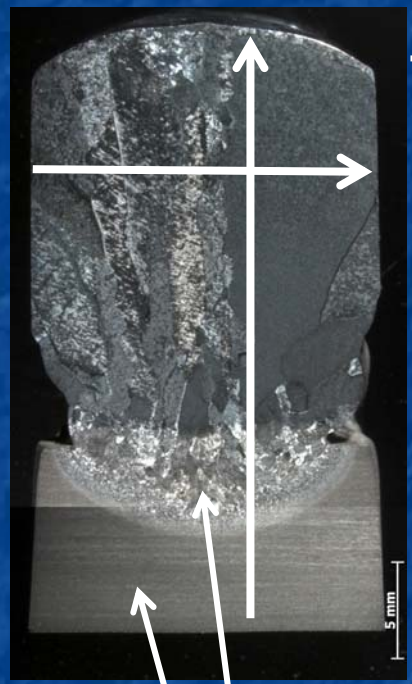
Significance of Process Parameters: Ranking and Interactions



- WF had strongest impact on Al content (WF >> BP, TS)
- BP & TS had minimal effect, strong coupling results in 2nd largest Al loss
- All parameters and 2-level interactions > TS
- TS and 3-level coupling are statistically insignificant

Cynthia.l.lach@nasa.gov

Micro-Chemistry Analysis of Multi-bead (10) Deposit:

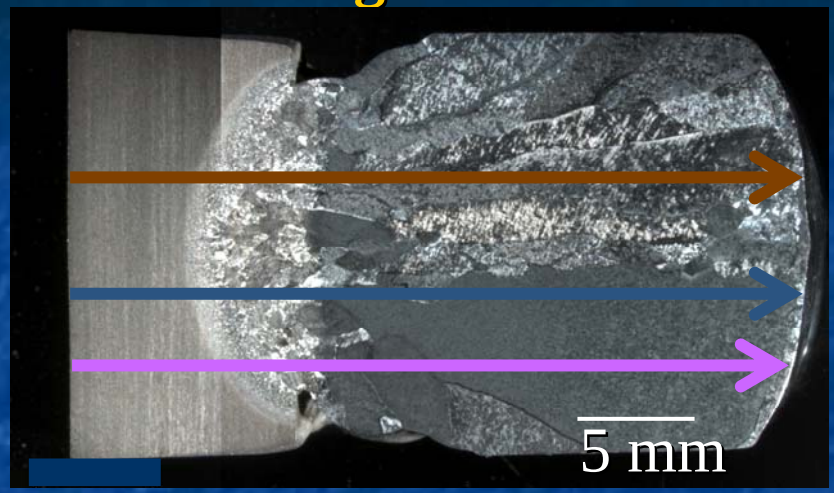


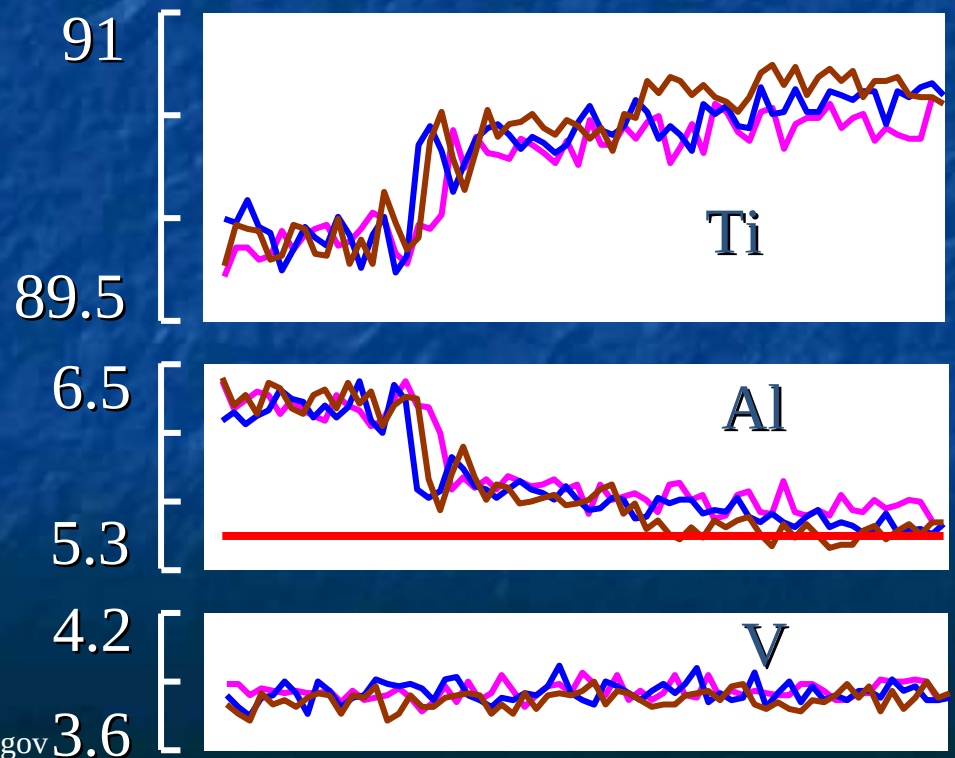
- Deposit was 10 beads high; fabricated at NASA LaRC
- Wavelength Dispersive Spectroscopy (WDS) using a scanning electron microscope (SEM)
- Higher fidelity than energy dispersive spectroscopy
  - Automation allows scans at micron level increments
  - Standardization performed on base plate using bulk chemistry

Cynthia.l.lach@nasa.gov

Micro-Chemical Results of Multi-bead (10) Deposit: BP=High TS=Low WF=Medium

WDS Line Scan in 500 μm increments

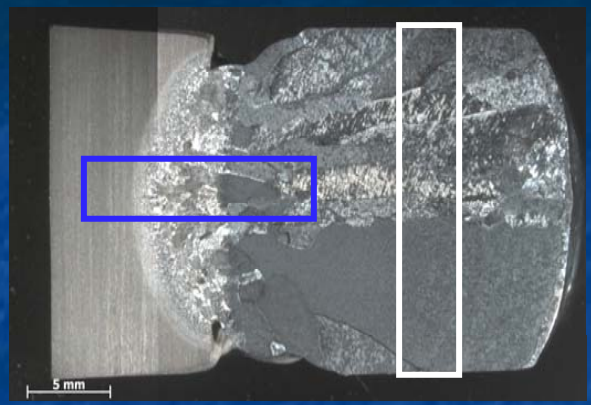




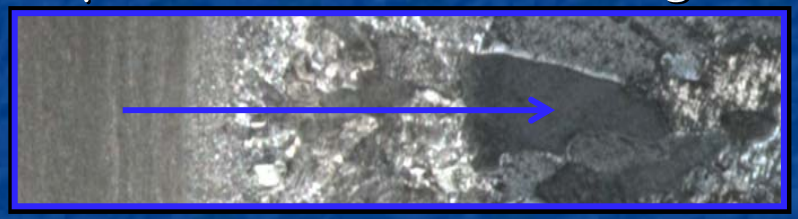
- Discrete change in Al and Ti Wt % at base plate/bead intersection
- Slight loss of Al through deposit
- Al loss independent of microstructure and bead interfaces
- V is unaffected by EBF^3 process

Cynthia.l.lach@nasa.gov

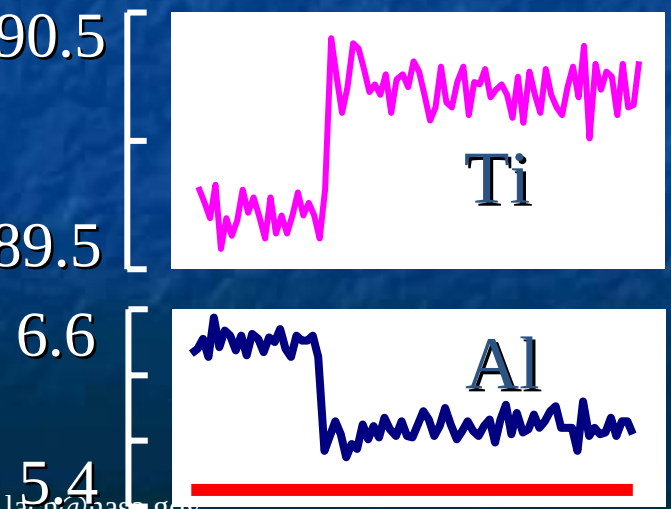
Micro-Chemical Results of Multi-bead (10) Deposit: BP=High TS=Low WF=Medium



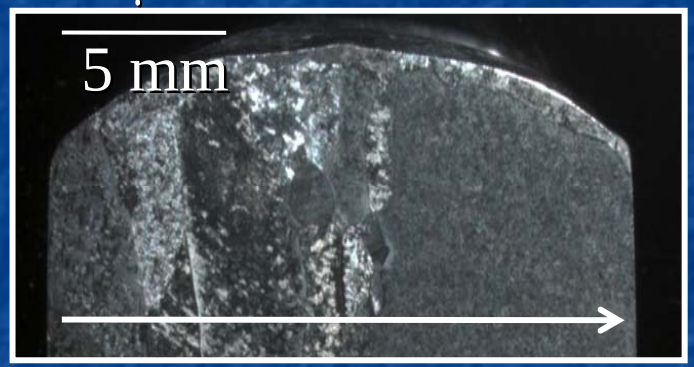
100 μm increment across mixing zone

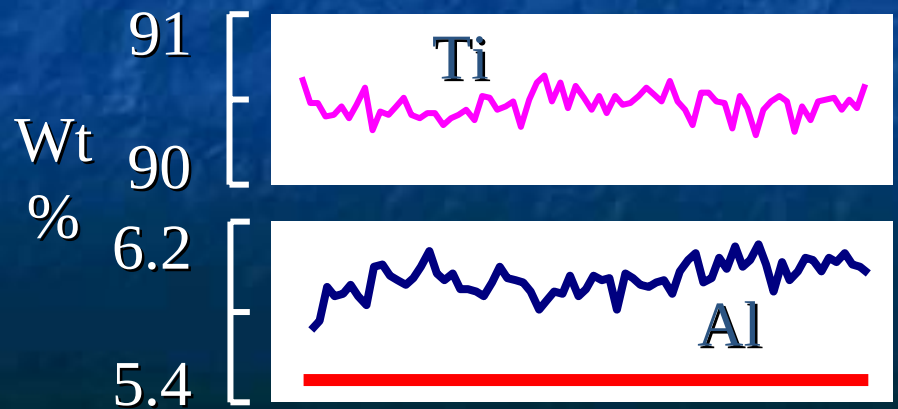


5 mm

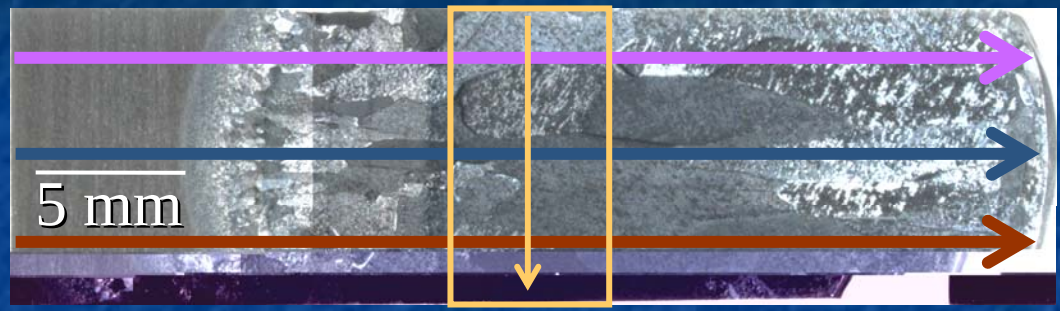


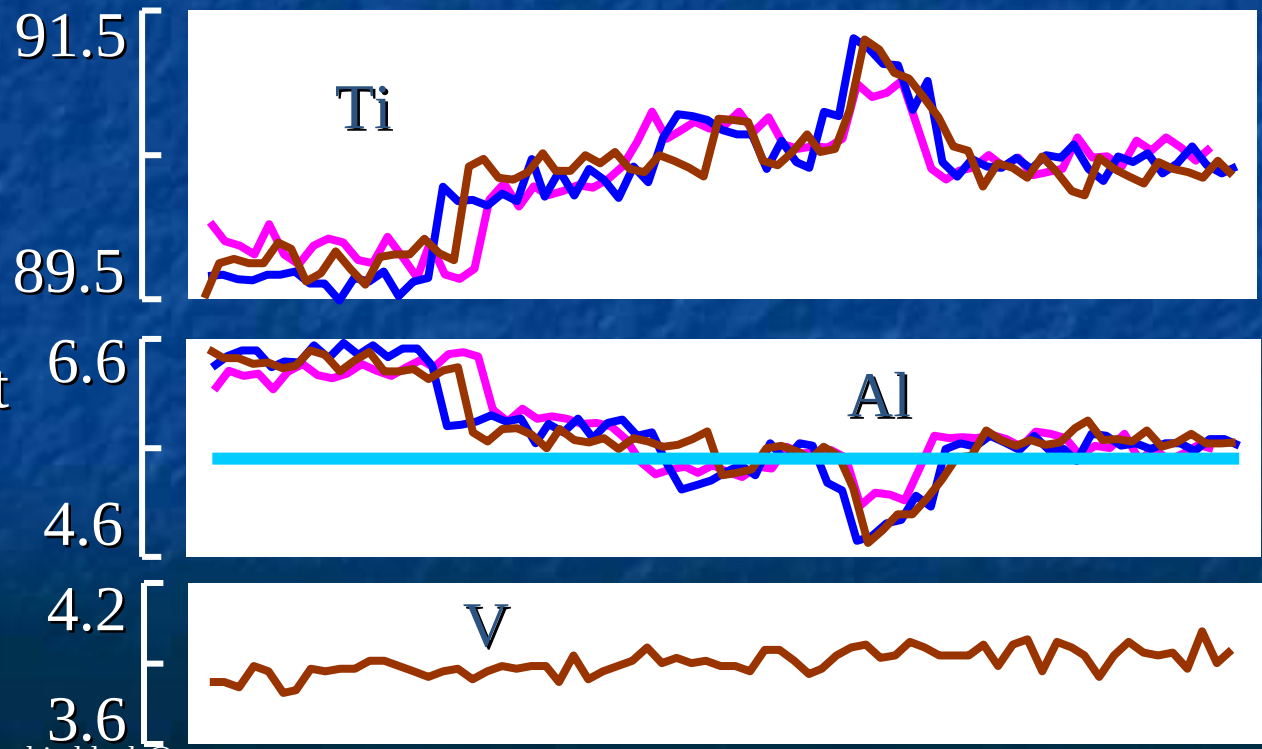
250 μm across width of bead

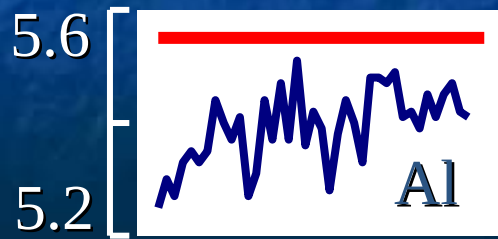




Micro-Chemical Results of Multi-bead (10) Deposit: BP=Medium TS=Low WF=Medium







Cynthia.l.lach@nasa.gov

Bulk Composition Results of Single-bead Deposit Ti-6-4 EBF^3 DOE (3 factor x 2 level)

Effect of process parameters on Al Loss

Individual impact of Parameters (BP, TS and WF):

- **WF has greatest impact on Al loss (WF>>BP,TS)**
- **BP also plays a significant role**
- **TS is insignificant**

Impact of Parameter Coupling:

- **WF and all 2-level interactions had more impact on Al loss**
- **than either BP or TS**
- **BP and TS separately had minimal effect but together caused 2nd largest Al loss**
- **TS was equivalent to the 3-level coupling and both were insignificant**

Micro-Chemistry Results of Multi-bead Deposit (10)

Effect of reducing BP while holding TS and WF constant

- **Discrete change in Al and Ti wt% at the base plate and deposit intersection**
- **Slight loss of Al through deposit**
- **Al loss is independent of microstructure and bead interfaces**
- **V content is unaffected by the EBF^3 process**

Future Work

- Complete DOE composition study for bulk and micro chemistries
  - Conduct micro-chemistry of single-bead deposits
- Examine bead microstructure and geometry resulting from processing parameters
- Develop better understanding of the effect of energy density level on bead geometry and chemistry